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Beam based alignment at LEP

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Abstract

We describe a beam-based method for finding the relative offset between beam position monitors (BPMs) and the magnetic centres of the adjacent quadrupole magnets. The strength of a given quadrupole is modulated and the induced closed orbit oscillation measured for different beam positions, reaching a minimum when the beam is centred in the quadrupole. The BPM reading at this point is a measure of its offset, which may be determined at LEP with an accuracy of $\sim$40 μm.

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Keywords: Beam-based alignment

1. Introduction

Decays of W bosons have been studied at the LEP collider at CERN since 1996. Production of a W^+W^- pair requires a centre of mass energy of 160.6 GeV and the goal of 100 GeV per beam was surpassed during the 1999 LEP running period. For precise determination of the W mass, the target for beam energy calibration is to reduce the uncertainty to below 15 MeV per beam.

Below 60 GeV at LEP, the technique of resonant spin depolarisation (RDP) is used to calibrate the beam energy [2]; this is the most accurate technique available. Electrons and positrons circulating in a storage ring tend to polarise their spins transversely to their direction of motion due to the Sokolov–Ternov effect [3]. The spins precess in the fields of the bending magnets, performing ν revolutions about the vertical bending field axis for one revolution about the ring. The quantity ν is referred to as the spin tune and is a precise measure of the beam energy [1].

Any quadrupole magnet through which the beam passes off-centre in the vertical direction will cause a perturbation of the spin direction, leading to depolarising resonances, the strength of which scales with γ^2 where $\gamma = E/E_0$. This makes it difficult to achieve an adequate level of polarisation above 60 GeV. RDP cannot, therefore, be used at LEP at the highest energies. Instead, the bending magnetic field is measured around the ring, using nuclear magnetic resonance (NMR) probes. This measurement is calibrated against

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RDP to give the average beam energy up to ~60 GeV; thereafter an extrapolation is used.

In order to achieve polarisation at as high an energy as possible, the technique of harmonic spin matching (HSM) is used [4]. It is possible to compensate the Fourier components of the vertical orbit by means of closed vertical orbit bumps which reproduce the perturbations with opposite phase. This involves calculation of the Fourier transform of the vertical orbit measurements, so that for the success of the procedure, accurate knowledge of the vertical orbit is essential [13].

The vertical orbit is measured by beam position monitors (BPM) mounted mechanically on the quadrupoles themselves. Fig. 1 shows a schematic of a BPM mounted on a quadrupole, with associated misalignments. Here, $\Delta_{y,k-\mathrm{mod}}$ denotes the offset measured by the alignment technique described in this paper. For the HSM to compensate depolarising resonances, misalignment of quadrupoles and of the BPMs with respect to the quadrupoles must be minimised. The technique of k-modulation is used to minimise the latter, which may be stem from mechanical or electronic sources. This technique may also be used for horizontal alignment and has been applied during normal machine operation.

Fig. 2 illustrates the principle of the technique. Considering a quadrupole magnet as a thin lens, a small sinusoidal perturbation of the current will cause the focal length to vary slightly with time. For a beam through the centre of the lens, this will make no difference to the beam centroid, whereas a beam passing off-centre will be modulated. The further is the beam from the lens centre, the greater will be the amplitude of the modulation. The amplitude is minimised when the beam is centred in the lens. At LEP, the position of the beam in a given quadrupole is scanned using

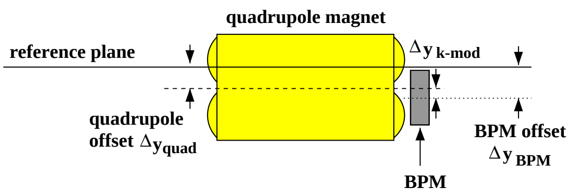

Fig. 1. Offsets of quadrupole magnets and their BPMs.

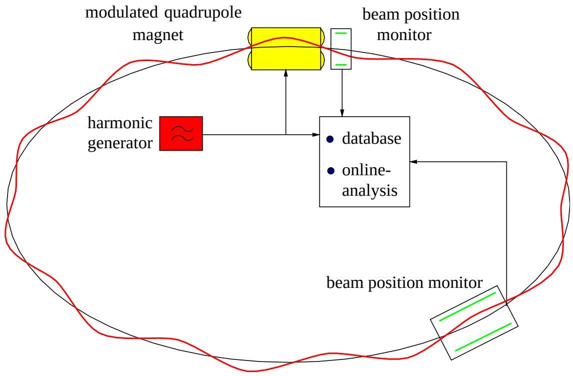

Fig. 2. Principle of k-modulation.

corrector magnets and the modulation detected simultaneously in two sensitive stripline beam position monitors located elsewhere in the ring. Plotting the amplitude of the closed orbit oscillation versus the beam position in the quadrupole yields a V-shaped distribution with a minimum where the beam is centred. The reading of the quadrupole's BPM when the beam is thus centred is a measure of the BPM offset with respect to the magnetic centre of the quadrupole. It is possible to determine the offset of several BPMs simultaneously by using a different excitation frequency for each one. The purpose of this paper is to describe the k-modulation technique in some detail and to examine the accuracy of the BPM offset determination.

2. Hardware for k-modulation

2.1. Magnet excitation

At LEP, only a small number of quadrupoles close to the interaction points are equipped with their own power converters. The remainder of the quadrupoles in the straight sections are powered in pairs on either side of the interaction point, whilst in the arcs the focusing quadrupoles are powered in one series and the defocusing quadrupoles in another.

In order to allow modulation of individual magnets, they are each equipped with an additional winding, known as the "back-leg winding".

This consists of a cable containing 8 copper strands of 0.75 mm^2 cross-section, wound once around the poles on top of the main windings of the magnet. The strands are connected in such a way as to form 8 turns. A power converter is provided on each side of each interaction point to excite harmonically the back-leg windings with currents of up to ± 6 A peak at frequencies between 0.72 and 50 Hz. One cable is used to carry the current, the excited magnet being selected by a diode switching matrix and a relay, connected to a separate multi-way selection cable.

It was found that the changing current in the back-leg winding could induce a voltage on the main winding of the quadrupole. At low rates of change, the power converter for the main winding was able to maintain a constant current. However, if the modulation frequency was sufficiently high, the current in the main winding was perturbed, thus affecting the other magnets in series. This problem was less severe for the arcs, with a large number of magnets in series, than for the straight sections, with the magnets in pairs. The modulation frequency was kept below a few Hz to avoid this effect.

Until 1998 the magnet excitation for the resistive magnets was not synchronised with the k-modulation data acquisition system. However, the excitation hardware included a timing module [5]. In 1998 such synchronisation was implemented, allowing the phase of the oscillation to be determined. As the beam crosses the centre of a quadrupole, the kick it receives from the modulation changes direction, so that the detected beam oscillation changes phase by π. The phase information may be used as a cross-check of the centreing of the beam in the quadrupole.

2.2. The beam position monitors

As the position of the beam in the quadrupoles is changed by the closed orbit bumps, it is measured using the BPMs, of which there are 504 at LEP, mounted mechanically on the quadrupoles themselves. These are part of the LEP beam orbit monitor (BOM) system [6]. Each BPM consists of four 34 mm diameter stainless steel button electrodes mounted in the LEP vacuum chamber.

Two different types of electronics exist for the readout of the BPMs, wide-band and narrow-band. The wide-band type is used for the four BPMs nearest the IP on each side. This is due to the electron and positron bunches passing each other with only a small time spacing close to the IPs. Further away from the IPs, the bunches are separated further in time and the response of the narrow-band electronics is sufficient. The gain of the wide-band type is switched according to the beam current whereas the gain of the narrow-band type is self-adjusting. The wide band type uses a 12 bit ADC to digitise the output of each electrode. For the narrow band electronics, an 8 bit flash ADC is used to digitise the difference signal for diagonally opposite pickup electrodes. In the latter case, the position resolution is 16 μm in the vertical direction and 11 μm in the horizontal, achieved by a Vernier technique. This increases the effective resolution to 11 bits by ramping the input pedestal of the FADC by 1/8 bin on each revolution period.

2.3. Detection of the closed orbit oscillations

The orbit oscillations induced by the modulated quadrupoles are detected by two sensitive pickups, installed to the left and right of LEP interaction point (IP) 1 [7]. The sensitivity of the pickups must be adequate to detect the oscillations in the orbit induced by the quadrupole modulation. These oscillations are kept to a few microns to avoid disturbing the LEP performance; thus, the electrodes are made in the form of 18 cm long 50 Ω strip lines. The k-modulation measurement makes use of the difference signal in an opposite pair of electrodes. Since the pickups are of a directional coupler type, we will refer to them as "couplers" to avoid confusion with the LEP BPMs whose offsets are to be measured.

In a circular accelerator, a kick to the beam $\Delta y'$ at position s_1 causes an orbit displacement y at a monitor at position s_2 according to [8]

$$y(s_2) = \frac{\sqrt{\beta(s_1)\beta(s_2)}\cos(|\mu(s_1) - \mu(s_2)| - \pi Q)}{2\sin(\pi Q)}\Delta y'(s_1) \tag{1}$$

where $\beta(s_1)$, $\beta(s_2)$ are the beta functions at the quadrupole and monitor, $\mu(s_1)$, $\mu(s_2)$ the phase advances and Q the betatron tune in the vertical plane. It can be seen that the phase advance between the quadrupole and the monitor may be such that the cosine term vanishes and no modulation is detectable. Two couplers separated by a suitable phase advance are used to guarantee that any modulation will be detectable.

2.4. Data acquisition

When a bunch passes through the coupler, a signal proportional to the beam position and current is measured; an average is taken over many turns and the averages stored in memory. The amplitude of the modulation is found by performing a harmonic analysis with a window around the excitation frequency.

The data acquisition electronics [9] is triggered by LEP with a frequency of 4 times the 11 246 Hz revolution frequency. This gives a trigger spacing of 22 μs. The trigger synchronises a gate with the passage of a bunch through the coupler. The signal within the gate is digitised in 13 μs, so that all bunches may be measured when LEP is operated with 4 bunches per beam.

The digitisation proceeds as follows. Each coupler signal is integrated by an integrate and hold (I/H) unit, which shares the trigger with the gate. The I/H output is then digitised by a 12 bit ADC and the result fed to a digital signal processor (DSP). The DSP is installed in a VME crate and reads out 8 ADCs (since we have 2 couplers, 2 particle types and 2 planes), summing over the readings taken. A 68030 microprocessor running the OS9 operating system divides the sum by the number of readings and passes the results to a UNIX workstation in the LEP control room. The workstation runs software which corrects for changes in the beam current which occur as a function of time during a fill and is also used for the online data analysis.

3. Data Analysis

A set of data for one coupler, plane and particle type consists typically of 2048 points, corresponding to the beam position in the coupler over 18 or 36 s, depending on the sampling frequency. A FFT is performed on the dataset to obtain the spectrum of modulation frequencies detected [9,10]. The amplitude may only be calculated exactly if the frequency is a multiple of f_{bin}, where $f_{\mathrm{bin}} = f_{\mathrm{s}}/N_{\mathrm{data}}$; f_{s} is the sampling frequency and N_{data} is the number of data points. If the frequency is not a multiple of f_{bin}, the calculated amplitude becomes frequency-dependent [11]. For this reason, the FFT is only used for online calculation and display purposes and a harmonic analysis is used to extract the oscillation amplitude more exactly.

3.1. Harmonic analysis

A discrete fourier transform (DFT) [12] is used to calculate the amplitude of the harmonic oscillation

$$u(t) = A\cos(2\pi f t + \phi). \tag{2}$$

This result is correct if the frequency is less than the Nyquist frequency. The transform is based on the function

$$\tilde{u}(f) = \sum_{k=0}^{N-1} u(t_k)\mathrm{e}^{-2\pi \mathrm{i} f t_k} \tag{3}$$

where $u(t_k)$ is the transverse beam position sampled at equidistant times $t_k = k\tau$. Now $\tilde{u}(f) = C(f) + \mathrm{i}S(f)$, where

$$C(f) = \sum_{k=0}^{N-1} u(t_k)\cos(2\pi \mathrm{i} f t_k) \tag{4}$$

and

$$S(f) = \sum_{k=0}^{N-1} u(t_k)\sin(2\pi \mathrm{i} f t_k). \tag{5}$$

The amplitude A and phase ϕ may then be reconstructed according to

$$A(f) = \frac{2}{N}\sqrt{C^2(f) + S^2(f)} \tag{6}$$

and

$$\phi(f) = -\arctan\left(\frac{S(f)}{C(f)}\right). \tag{7}$$

The result is independent of frequency for a sufficiently large number of data points.

3.2. Sampling effects

There may be, however, problems with aliasing, for example due to signals from betatron oscillations. Such frequencies above the Nyquist limit may cause distortion of the signals below the limit. This is avoided by averaging the beam position for n_{av} bunches, which is equivalent to the use of a low pass filter. Instead of one measurement every time interval τ, the mean of n_{av} measurements is used and the function $u(k\tau)$ is replaced by

$$\bar{u}(k\tau) = \frac{1}{n_{\mathrm{av}}} \sum_{j=0}^{n_{\mathrm{av}}-1} u\left(\left[k + \frac{j}{n_{\mathrm{av}}}\right] \cdot \tau\right). \tag{8}$$

It can be shown that the calculated amplitude of an oscillation of frequency f is attenuated by

$$a(\xi) = \left|\frac{\sin(\pi\xi)}{n_{\mathrm{av}} \sin(\pi\xi/n_{\mathrm{av}})}\right| \tag{9}$$

where $\xi = f/f_{\mathrm{s}}$.

3.3. Windowing

The use of the raw data for the harmonic analysis corresponds to a rectangular window [11]; if the modulation frequency is not a multiple of the frequency f_{bin}, artificial signals will appear in adjacent bins. This is termed spectral leakage. Since we are only able to use a small range of frequencies for the magnet excitation and we wish to excite several magnets simultaneously, this spectral leakage must be minimised.

In order to reduce the spectral leakage and hence increase the frequency resolution, a windowing function is applied to the raw data. The ith data point is weighted by the factor $w(i)$, which depends on the windowing function used. The so-called Hamming window [11] was selected as the most suitable for this application, with

$$w_{\mathrm{Ham}}(i) = 0.53856 - 0.46144\cos(2\pi i/N_{\mathrm{data}}). \tag{10}$$

The spectral leakage is most likely to cause problems if the beam is well centred in one quadrupole, resulting in a small signal, and badly centred in another, resulting in a large signal. Such a situation was simulated in [10], for two signals with amplitudes $A_1 = 1.0$ and $A_2 = 0.1$, with frequencies $f_1 = 1.52$ Hz and $f_2 = 1.68$ Hz. The harmonic analysis with the Hamming window allowed the two signals to be separated, whilst with the rectangular window, the smaller signal was obscured. The sampling frequency was 112.46 Hz, with 2048 data points.

In order to avoid problems with crosstalk, the magnet excitation frequencies must be separated by more than some minimum frequency spacing Δf_{min}. For the Hamming window, a value of $\Delta f_{\mathrm{min}} = 2.5 f_{\mathrm{bin}}$ was found to be sufficient, giving a value of 0.137 Hz for the above case.

3.4. Cuts

A plot of coupler signal versus orbit position is expected to yield a V-shaped distribution, centred about a value which represents the offset of the BPM relative to the quadrupole [14]. This may be a combination of a mechanical and/or an electronic offset. Before making such a plot, it is necessary to consider the effects of orbit oscillations from sources other than the magnet excitation, for example from orbit drifts and corrections.

A change of orbit during the measurement can lead to a data point which does not lie on the V-shaped distribution. The orbit position assigned to such a point can be that due to the orbit before the change, whilst the coupler signal can be that after the change. The same situation can occur between the orbit bumps used to scan the beam position through the quadrupole magnet. In order to reject such points, the difference in orbit position is examined for consecutive orbit position readings during the measurements. If a step greater than a threshold value is found, the points before and after the change are discarded.

In addition, a further cut is made to exclude data with low frequency components. During the recording of data from the coupler, orbit corrections or drifts may cause the position of the beam in the quadrupole to change. Thus, the orbit position stored by the data acquisition will no longer represent the real situation. Such changes will also induce a low frequency signal in the couplers. If this is of sufficient magnitude, it may distort the result of the harmonic analysis. For these reasons, the amplitudes of first three bins in frequency above DC of the FFT are summed and data where the sum exceeds a given value rejected. This then excludes from the analysis data which may have been affected by slow beam movements.

The signal from the k-modulation must be analysed in the presence of possible beam oscillations from other sources. This is of particular concern when the beam is well-centred and the signal which we wish to analyse is small. A cut is therefore applied on the difference between the excitation frequency, which is stable, and the peak frequency value returned by the harmonic analysis, which may be perturbed.

Therefore, the harmonic analysis is performed firstly at the excitation frequency $f_{\rm mod}$ and the two frequencies $f_{\rm mod} \pm 0.1$ Hz. The frequency returning the greatest amplitude is then taken as the new centre frequency, the frequency spacing halved and the process repeated. Four iterations are performed and the resulting uncertainty on the frequency of the maximum is 0.00125 Hz. In the subsequent data analysis, data are accepted only if the detected signal falls within 0.018 Hz of the modulation frequency.

3.5. BPM offset determination

During the measurement, closed orbit bumps are used to scan the beam across the centre of the quadrupole magnet. Typically, bumps from -1 mm to $+1$ mm in steps of 0.5 mm are used if the LEP experiments are taking data, to avoid the perturbation of the beam leading to a fall in luminosity. In 1998, dedicated machine development time was allocated to k-modulation measurements and bumps from -2 mm to $+2$ mm in steps of 1 mm were used.

After the data have been accumulated and the cuts performed as described, fitting is performed in order to extract the offset of the BPM with respect to the magnetic centre of the quadrupole. According to (1), the strength of the detected signal will be linear with offset. Plotting coupler signal $A(y)$ versus orbit position y, we thus obtain a V-shaped distribution of data points with the minimum of $A(y)$ corresponding to the offset y_0 (see Fig. 3). This is then fitted with the function

$$A(y) = a|y - y_0| + A_0 \tag{11}$$

where the parameter A_0 is included to take into account noise sources which may introduce a non-zero minimum of $A(y)$.

Each V-shaped distribution has been fitted using the minimisation program MINUIT [15,16], which requires as an input a realistic error estimate in the vertical direction for the data points, if the errors on the parameters returned by the fit are to be meaningful. Hence, the overall error on the fit has been estimated by first assigning to each point a constant error term in the vertical direction. This error term was then scaled to give a χ^2 per degree of freedom close to 1, on average over all the individual fits. A value close to 3 μm was selected and used to re-fit the data. This resulted in statistically meaningful errors on the calculated offsets, which were used in the subsequent analysis to make cuts, selecting only reliable offset values.

It is also possible to plot the phase of the oscillation, which may be fitted with the function

$$P(y) = \arctan[(y - y_0)a] + P_0 \tag{12}$$

from which it is seen that the phase changes through π as the beam crosses the magnetic centre of the quadrupole. This type of fit has not yet been used in offset determination, but provides a useful cross-check that the beam has indeed crossed the centre. The accuracy is limited by noise close to the transition.

4. Results

In 1997, the k-modulation measurements were performed parasitically during physics data taking. The machine optics used a 90/60 deg horizontal/vertical phase advance per cell and a total of 419 offset measurements were performed. Data were recorded for both electron and positron beams. In 1998, dedicated machine time was available for the k-modulation measurements. Optics with a 60/60 deg horizontal/vertical phase advance were used, with an electron beam only. This is the same situation as is used for the polarisation-based energy measurement. A total of 289 offsets were determined. In addition, a small number of measurements were performed

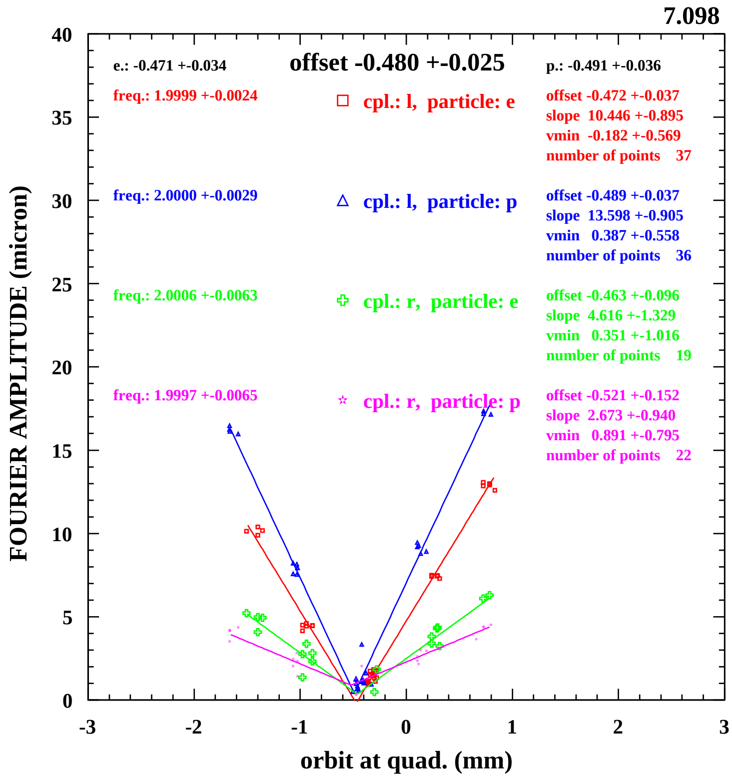

Fig. 3. Determination of a single BPM offset (1997).

parasitically; physics conditions used a 102/90 deg phase advance in 1998.

Fig. 3 shows the offset determination from one quadrupole magnet in 1997. Four offsets are shown, calculated from the signals from each the two couplers for both particle types. In this case, the phase was adequate at both couplers to give an offset determination from each coupler. The offset determinations agree to the level of $\sim 20\ \mu\text{m}$. Each combined offset value was calculated as the mean of the individual values, weighted by their separate errors. The combined error ε was calculated from the errors on the fits ε_i as

$$\varepsilon = \left[\sum_{i=1}^{n} \frac{1}{\varepsilon_i^2}\right]^{-1/2}. \qquad (13)$$

Combined offsets and their associated errors were calculated for electrons, for positrons and overall. A histogram of the calculated overall errors on the 1997 data is shown in Fig. 4. Since it is undesirable to include faulty offset determinations in the LEP database, a cut of $55\ \mu\text{m}$ was applied to the calculated error on the offset determinations. In addition, it was required that the offset as measured with positrons minus that measured with electrons lie within the range $-100\ \mu\text{m}$ to $200\ \mu\text{m}$. Fig. 5 shows the motivation for this asymmetric cut; there is a systematic difference between the offsets measured with the two particle types. This is not due to a real difference in orbit between the two particle types but is due to an asymmetry in the response of the electronics of the beam position measurement system. After the cuts, the offset for electrons and that for positrons were entered into separate reference tables; for those which were rejected, the entries in the database were set to zero. Figs. 6 and 7 show histograms of the offsets for electrons and positrons after the cuts were performed on the 1997 data.

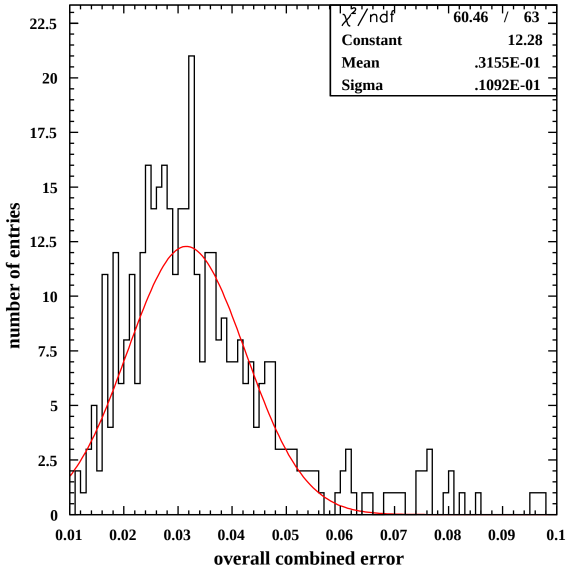

Fig. 4. Calculated errors on BPM offsets (1997).

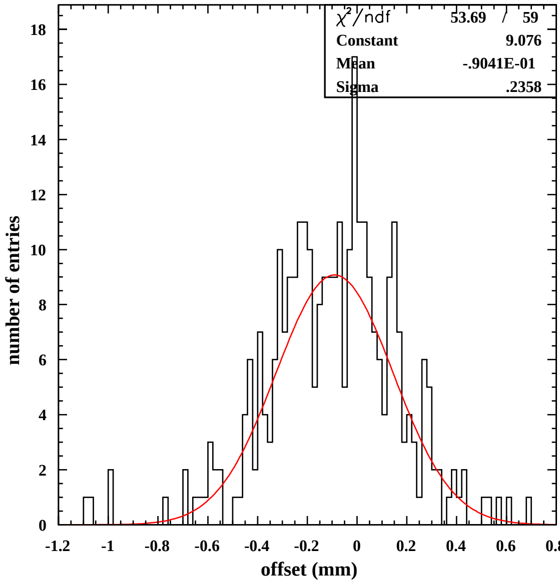

Fig. 6. Offsets measured for e− after cuts (1997).

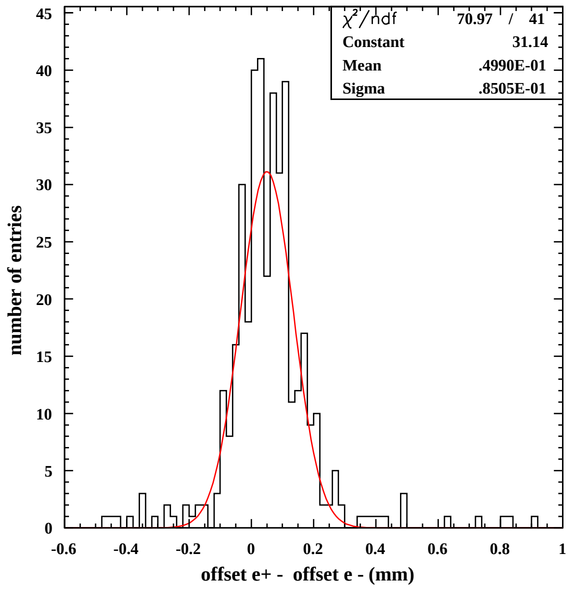

Fig. 5. Difference between e− and e+ offsets (1997).

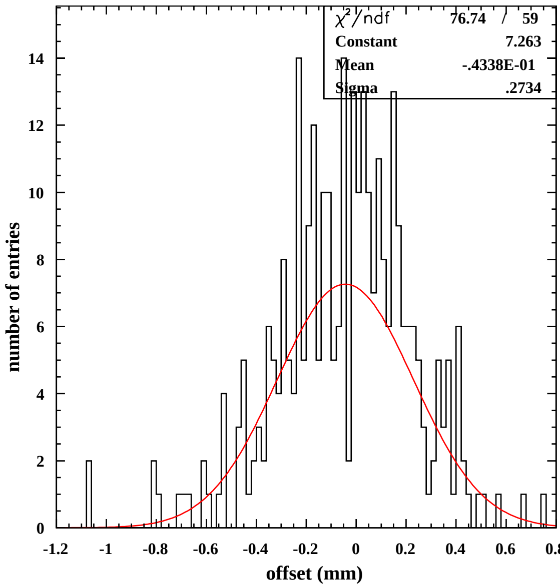

Fig. 7. Offsets measured for e+ after cuts (1997).

For the 1998 data, a cut of 70 μm was applied to the error calculated from the fit for each coupler. At least one good coupler signal was required. A histogram of all the offsets after the cuts is shown in Fig. 8. For 1998, only a small number of measurements were taken parasitically, so that the bulk of the offsets are for the electron beam only, recorded under the same conditions as for the energy measurement by resonant depolarisation.

The histograms of the offsets for electrons for the two years are shown after fitting with Gaussian distributions. The σ of the distribution was found

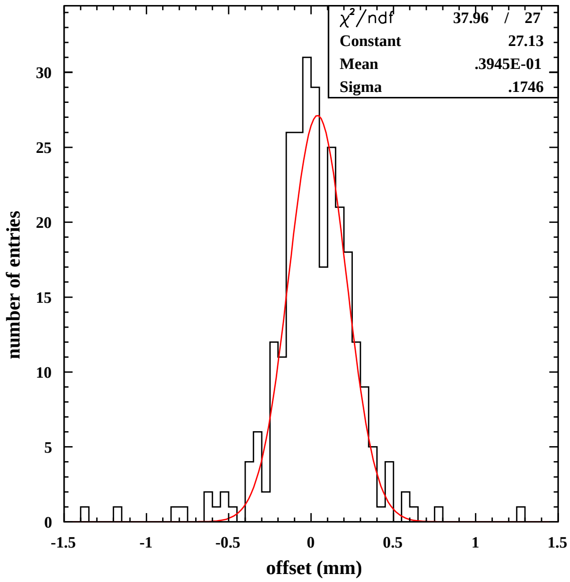

Fig. 8. Offsets after cuts (1998).

to be 236 μm for the 1997 data and 175 μm for the 1998 data. Now the 1998 data was measured with the 1997 offsets already loaded in the LEP database. The difference in σ between the two years is a measure of the combined effects of changes in offset and any inaccuracy of the k-modulation technique. If the assumption can be made that the offsets are stable from year to year, one can estimate the accuracy of the offsets from the σ of the 1998 data for those BPMs which were measured in both years.

4.1. Error estimation by comparing the years

For those offsets which were determined in both years, the measured offset $y_{0\,i}$ in a given year for the ith quadrupole was the real offset plus an error term

$$y_{0\,i} = y_{\mathrm{bpm}\,i} + \Delta_i \tag{14}$$

if the bpm offsets have not changed, the real offset in 1998 is just the error term from 1997, since the offsets measured in 1997 have been entered in the LEP database. So the measured offset in 1998 is just the total error for the 2 years

$$y_{0\,i} = \Delta_i^{97} + \Delta_i^{98} \tag{15}$$

thus, the spread of the offset distribution in 1998 is the combined spreads of the errors for the two years

$$\sigma_{y_0}^{98} = \sigma_\Delta^{97} \oplus \sigma_\Delta^{98} \tag{16}$$

if the errors are equal from year to year, we can estimate the error on the offset determination to be

$$\mathrm{err}(y_0) = \frac{1}{\sqrt{2}}\sigma^{98}_{\mathrm{meas\ \ offset}} \tag{17}$$

since $\sigma_{y_0}^{98} = 175$ μm we arrive at an error estimate of 124 μm.

4.2. Error estimation by comparing couplers

It is also possible to estimate the error by comparing the offsets measured using the two couplers. Figs. 9 and 10 show histograms of the difference between the offset determined using the left coupler only and that using the right coupler only, for the 1997 data. The same histogram for the 1998 data is shown in Fig. 11. The data in these plots were selected by demanding that the calculated error for both couplers be smaller than a given value. This was set at 150 μm in 1997 and 70 μm in 1998, the difference being due to the

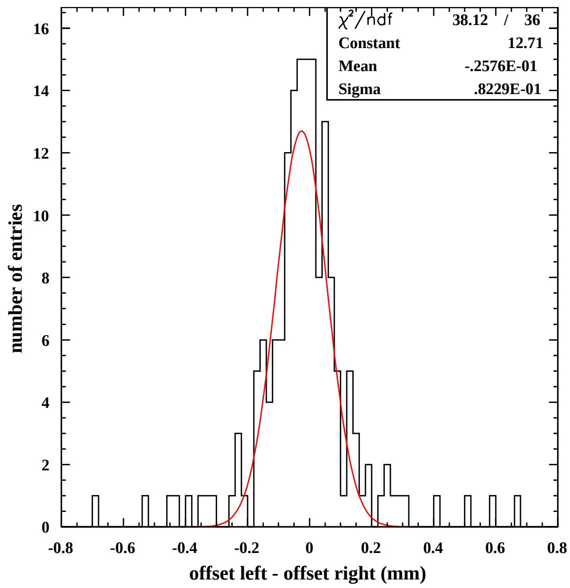

Fig. 9. Difference in offsets between left and right couplers, e− (1997).

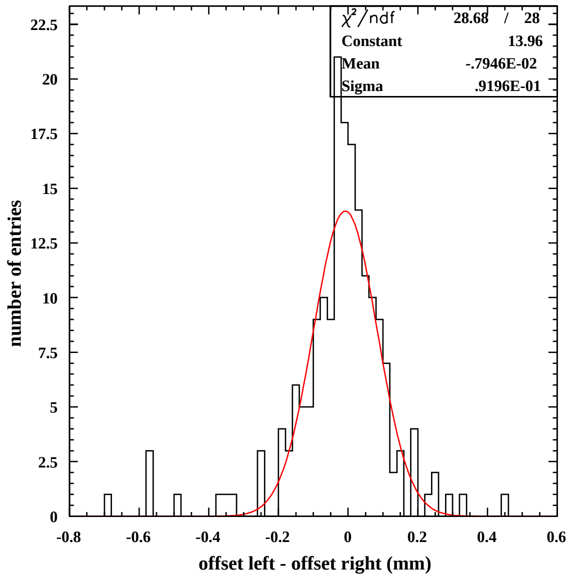

Fig. 10. Difference in offsets between left and right couplers, e+ (1997).

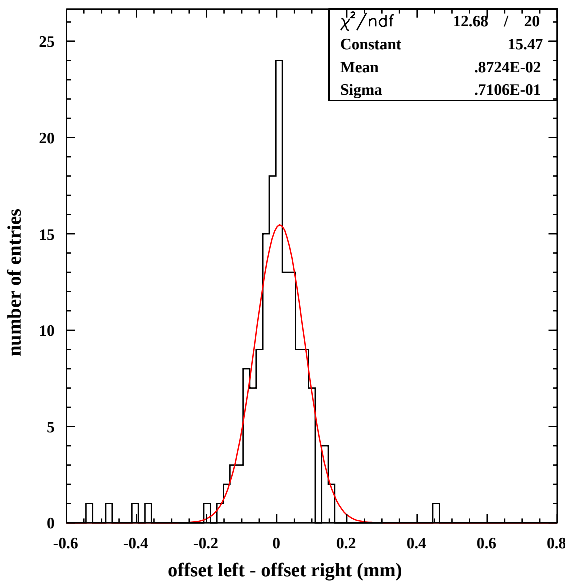

Fig. 11. Difference in offsets between left and right couplers, e− (1998).

greater slope of the V-shaped fit in 1998 leading to a smaller calculated error. It was also possible to compare the offsets measured for electrons and positrons for single couplers from the 1997 data (Figs. 12, and 13).

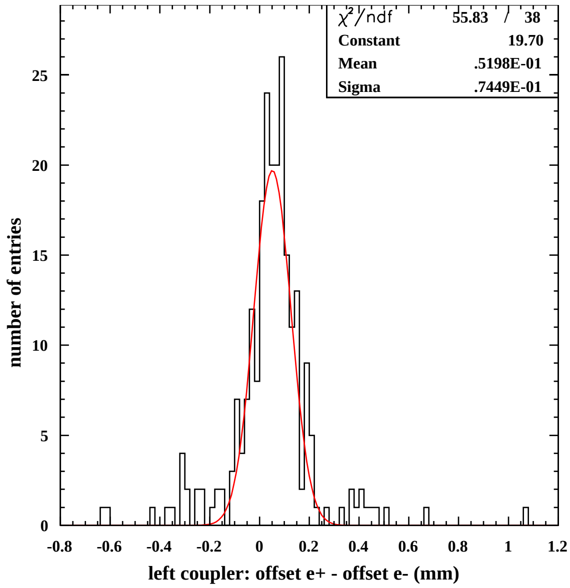

Fig. 12. Difference in offsets between e− and e+, left coupler (1997).

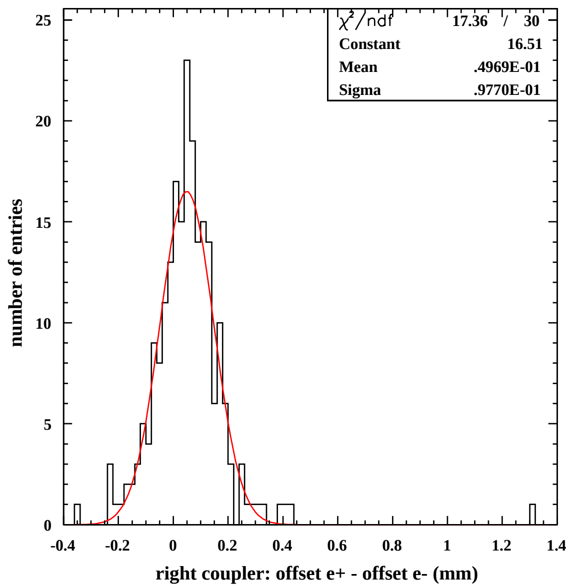

Fig. 13. Difference in offsets between e− and e+, right coupler (1997).

The σ of the histogram in each case is the error on the difference between the couplers and will be the individual coupler errors added in quadrature

$$\varepsilon_{\rm diff} = \varepsilon_l \oplus \varepsilon_r \qquad (18)$$

since we expect the errors for the couplers to be the same, the error on a single coupler will be

$$\varepsilon_{l,r} = \frac{\varepsilon_{\mathrm{diff}}}{\sqrt{2}} \tag{19}$$

the value entered in the database is the weighted mean for both couplers, for which the minimum error on the mean will occur when the phase is adequate to give a good fit for both

$$\varepsilon_{\mathrm{mean}} = \left(\frac{\varepsilon_{\mathrm{diff}}}{\sqrt{2}}\right)\frac{1}{\sqrt{2}} = \frac{\varepsilon_{\mathrm{diff}}}{2}. \tag{20}$$

The histograms were fitted with Gaussian distributions in order to give $\varepsilon_{\mathrm{diff}}$. For electrons, the 1997 data gave $\varepsilon_{\mathrm{diff}} = 82$ μm and for positrons $\varepsilon_{\mathrm{diff}} = 92$ μm. Comparing the offsets for electrons and positrons gave $\varepsilon_{\mathrm{diff}} = 74$ μm for the left coupler and $\varepsilon_{\mathrm{diff}} = 98$ μm for the right coupler. In 1998, only comparison between the two couplers for electrons was possible, which led to $\varepsilon_{\mathrm{diff}} = 71$ μm.

Thus, for measurements for which the phase in both couplers was adequate, the accuracy of the offset determination was 43 μm for 1997 and 36 μm for 1998.

4.3. Reproducibility

In 1998, repetitive measurements were carried out on 4 quadrupole magnets, in order to examine the reproducibility of the offset measurements. The repetitive measurements were carried out parasitically towards the end of fills for physics. The number of quadrupoles modulated at any one time was kept small in order to minimise any disturbance to the luminosity. The different physics optics used in 1998 compared to that in 1997 was found to lead to greater luminosity disturbance.

Fig. 14 shows a histogram of the offset of one quadrupole magnet measured many times over a period of days. The offsets calculated for each coupler and particle type were treated as independent and were subjected to a cut of 80 μm on the error calculated from the fit. The histogram was fitted with a Gaussian distribution, whose σ is then an estimate of the error on a single measurement. The result was $\sigma = 57$ μm, leading to an estimate of the error on the mean of two couplers of 40 μm.

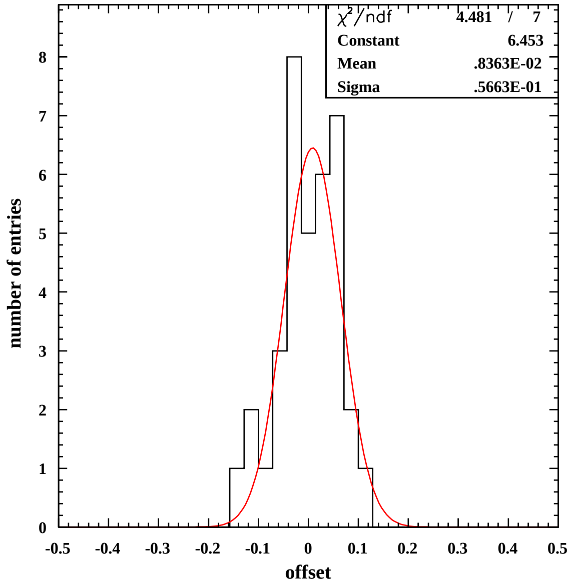

Fig. 14. Repetitive measurement of a single offset (1998).

Table 1

Histogram contents	Histogram σ(μm)	k-mod error (μm)
offset for e$^-$ ('97)	236	n/a
offset for e$^-$ ('98); '97 offsets in database	175	124
left coupler – right coupler, e$^-$ ('97)	82	41
left coupler – right coupler, e$^+$ ('97)	92	46
left coupler – right coupler, e$^-$ ('98)	71	36
offset e$^-$ – offset e$^+$, left coupler ('97)	74	37
offset e$^-$ – offset e$^+$, right coupler ('97)	98	49
Repetitive measure single offset, e$^-$ ('98)	57	40

4.4. Summary

Table 1 summarises the σ of each of the histograms used in calculating the accuracy of the k-modulation technique and the error obtained:

5. Conclusions

The technique of k-modulation to determine BPM offsets with respect the quadrupole magnets of LEP has been described. The hardware used and data analysis procedures have been detailed. It is of interest to know how accurately the offsets can be measured and how stable the measurements are with time. For the 1997 data, we have estimated the error on the measured offsets by comparing the results from the two couplers for the same offset, yielding a result of 43 μm when averaged over the results from e^- and e^+. The same procedure was carried out on the 1998 data and a result of 36 μm obtained. We expect some variation of achievable accuracy with machine optics, through changes in the slope of the V-shaped distribution. In 1998, the k-modulation error was also estimated by measuring repetitively a small number of offsets and a value of 40 μm extracted from the analysis.

The accuracy of the measurement was also examined by comparing the offsets from year to year, under the assumption that the offsets are stable. This leads to an error estimate of 124 μm. This is sufficiently large compared to the value extracted by the other methods that we conclude that there is in fact instability in the offsets on a timescale of 1 year. This may be mechanical or electronic in nature and may be affected by the BOM system recalibration, which is carried out periodically at LEP on a timescale of a few weeks.

The BPM offsets measured in 1998 were entered into the LEP beam orbit measurement system database and thus used to correct the BPM readings. Towards the end of 1998, after the entry of the offsets to the database, energy calibration by resonant depolarisation was performed. The knowledge of the offsets allowed a better correction of the orbit than had previously been possible, resulting in the minimisation of depolarising resonances. This allowed sufficient polarisation to be achieved at 60 GeV for energy calibration by resonant depolarisation to be successful for the first time at such a high energy.

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